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Space-based measurements of air quality during the World Expo 2010 in Shanghai

N Hao¹, P Valks¹, D Loyola¹, Y F Cheng² and W Zimmer¹

¹ Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Methodik der Fernerkundung, Oberpfaffenhofen, Germany

² College of Environmental Sciences and Engineering, Peking University, Beijing, People's Republic of China

E-mail: nan.hao@dlr.de

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Abstract

During the World Exposition 2010 (Expo, from May to October), emission control measures were implemented in Shanghai and surrounding areas to improve the air quality. To evaluate the effect of these measures, we use the tropospheric NO₂ column, aerosol optical thickness (AOT) and CO concentration observations from the satellite instruments GOME-2, MODIS and MOPITT, respectively. The analysis shows about 8% and 14% reductions of tropospheric NO₂ columns and AOT respectively over Shanghai during the Expo period, compared to the past three years. A 12% reduction of CO concentration at 700 hPa over Shanghai and surrounding areas is found during the Expo period. On the other hand, the satellite measurements show increases of NO₂ by 20% and AOT by 23% over Shanghai urban areas after the Expo (November 2010–April 2011), when the short-term emission control measures were lifted. Our study indicates that the air quality measures were effective in Shanghai and surrounding provinces during the Expo period.

Keywords: satellite, NO₂, aerosol, CO, world exposition, Shanghai

1. Introduction

Shanghai (31.2°N, 121.5°E), one of the largest cities in China, held the World Exposition 2010 (Expo) from 1 May to 31 October 2010. Its fast growing economy, long history of industrial development and rapid industrialization in neighboring provinces pose large challenges to the air quality in the Shanghai area. Chen *et al* (2006) reported that in Shanghai the power plants, industries and transportation contributed about 40%, 24% and 22% of NO_x emissions and about 34%, 46% and 7% of PM₁₀ emissions in 2000, respectively. They predicted that the transportation sector, which contributed about 30% and 18% of NO_x and PM₁₀ emissions respectively in 2010, would become increasingly important in the future. Using GOME and SCIAMACHY satellite measurements, van der A *et al* (2006) showed a yearly increase of 20% ± 6% in the tropospheric NO₂ columns over Shanghai during the period 1996–2005, compared to a yearly increase of 10% ± 4% in

Beijing. Based on ground-based measurements, Chan and Yao (2008) found that the local soot, SO₂ and NO₂ emissions in Shanghai were 2–3 times than those in Beijing during 2003–5.

The air quality during the Expo in Shanghai was a major concern for the local government, similar to that during the Olympic Games in Beijing. To improve the air quality during the Expo, the Shanghai municipal government pursued many emission control measures (ECMs) focusing on energy, industry, transport and construction (UNEP 2010). During the Expo period, short-term ECMs were brought forward for the main pollution sources that greatly affect the air quality in Shanghai. Similarly to during the Beijing Olympic Games (Wang *et al* 2009), several high polluting enterprises such as coking and cement industries were ordered to reduce their operating capacities and all construction activities in the city were suspended during the Expo. Meanwhile, agricultural burning was fully banned in Shanghai and the surrounding provinces because agricultural fires have a

significant influence on the air quality in Shanghai (Li *et al* 2010). Shanghai enforced some traffic control measures including implementation of new vehicle emission standards, replacement of older polluting cars, and access restriction of trucks and old cars entering into Shanghai (CAI-Asia 2010). Although no very strict traffic control measures (such as removing half of the cars from the road as implemented during the 2008 Beijing Olympic Games) were implemented during the Expo period because of its long duration, the NO_x emissions from vehicles would decrease by about 10%, as estimated by Shanghai Environmental Protection Bureau (2010). In addition, joint pollution prevention and control measures were carried out in the surrounding provinces (Zhejiang and Jiangsu Provinces) because air pollutants from the surrounding areas could also affect the air quality in Shanghai under certain meteorological conditions. A number of papers (e.g., Cheng *et al* 2008, Mijling *et al* 2009) have been published on the air quality changes during the Sino-African Summit and Olympic Games in Beijing measured by ground-based or satellite measurements, indicating the decrease of the measured pollutants because of ECM implementation. Satellite measurements showed significant decreases in tropospheric NO_2 (43%), SO_2 (13%) and CO (12%) during the Olympic Games (Witte *et al* 2009) and the emissions of NO_x over Beijing were reduced by 40% during the Sino-African summit (Wang *et al* 2007). However, these ECMs were only enforced for a short time period (from a few days to 1–2 months).

In this study, we use satellite measurements to monitor the evolution of major air pollutants in Shanghai and the surrounding areas: NO_2 , aerosol loading and CO. Their changes during and after the Expo are tracked using data from three satellite instruments: the Global Ozone Monitoring Experiment 2 (GOME-2), Terra's Measurements of Pollutants in the Troposphere (MOPITT) and Aqua's Moderate Resolution Imaging Spectroradiometer (MODIS). Meanwhile, comparisons between GOME-2 tropospheric NO_2 columns and *in situ* NO_2 measurements are also shown. The six-month duration of the Expo provides a unique opportunity to examine the effectiveness of ECMs on air quality over Shanghai and the surrounding provinces and to demonstrate the ability of satellite observation to monitor and quantify these changes.

2. Data and methods

To evaluate the effect of ECMs on the nitrogen oxides ($\text{NO}_x = \text{NO} + \text{NO}_2$) pollution during the Expo period, tropospheric NO_2 observations from the GOME-2 sensor are used. GOME-2 is a nadir-viewing scanning spectrometer on EUMETSAT's MetOp-A satellite, launched in 2006. It has a spectral coverage of 240–790 nm and a spectral resolution between 0.26 and 0.51 nm. GOME-2 observes four times smaller ground pixels ($80 \times 40 \text{ km}^2$) than its predecessor GOME on ERS-2, and provides a global coverage within about 1.5 days (Munro *et al* 2006). The MetOp-A satellite is flying on a sun-synchronous orbit and has an equator crossing time of 9:30 local time. Operational total and tropospheric NO_2 products

are routinely retrieved at the German Aerospace Center (DLR) in the framework of the EUMETSAT Satellite Application Facility on Ozone and Atmospheric Chemistry Monitoring (O3M-SAF) with the GOME Data Processor (GDP) version 4.4 (Valks *et al* 2010, 2011). In this study, monthly average GOME-2 tropospheric NO_2 data (horizontal resolution $0.1^\circ \times 0.1^\circ$) for the period of January 2007–April 2011 are used. The total uncertainty in the GOME-2 tropospheric NO_2 column is about 40% for polluted regions (Valks *et al* 2011). A first validation of the GOME-2 NO_2 product using MAXDOAS in Beijing indicated that the GOME-2 tropospheric NO_2 columns correlated well (correlation coefficient up to 0.81) with the ground-based data (Pinardi *et al* 2010).

Daily mean NO_2 concentrations in Shanghai are derived from the NO_2 air pollution index (API), which is the average of *in situ* measured NO_2 concentrations at nine monitoring stations from the Shanghai Environmental Monitoring Center (SEMC). The NO_2 API records for previous years (2000–6) have been used to compare *in situ* and satellite NO_2 measurements (Zhang *et al* 2007).

To analyze the aerosol loading during the Expo, the aerosol optical thickness (AOT) products from MODIS data have been used. The MODIS instrument onboard NASA's Aqua satellite (launched in 2002) has 36 spectral channels ranging from 0.4 to $14.4 \mu\text{m}$ representing three spatial resolutions: 250 m (2 channels), 500 m (5 channels) and 1 km (29 channels). Seven of these channels ($0.47\text{--}2.13 \mu\text{m}$) are used to retrieve aerosol characteristics (Remer *et al* 2005). The uncertainty of the MODIS AOT is within 20–30% (Levy *et al* 2007). Wang *et al* (2010) concluded that the MODIS aerosol products have good accuracy over China. Monthly averaged AOT values on a horizontal resolution of $1^\circ \times 1^\circ$ (MOY08 collection 5.1 (Levy *et al* 2007)) from January 2007 to April 2011 are analyzed in this work.

Atmospheric profiles of CO are measured by MOPITT (launched on 1999 onboard NASA's Terra spacecraft) using thermal radiation at $4.7 \mu\text{m}$ with a spatial resolution of $22 \times 22 \text{ km}^2$. Long-term MOPITT data have been used for monitoring the evolution of CO levels in Northeast Asia induced by both industrial activities and biomass burning (Choi and Chang 2006). In the present study, MOPITT V4 level 3 data (Deeter *et al* 2009) from January 2007 to April 2010 are analyzed. The monthly average CO mixing ratios on a horizontal resolution of $1^\circ \times 1^\circ$ at the 700 hPa level (instead of 900 hPa) are used because MOPITT has little sensitivity to CO within the boundary layer (BL, Deeter *et al* (2003), Emmons *et al* (2004, 2007)). Emmons *et al* (2004) showed that the MOPITT CO measurement precision above 700 hPa is about 10%.

To analyze the effect of the meteorological conditions on the tropospheric NO_2 and CO distribution as well as the aerosol loading for the Shanghai area, precipitation, temperature and wind data recorded by automatic weather stations situated at Hongqiao airport, Shanghai (31.2°N , 121.3°E), Pudong airport, Shanghai (31.1°N , 121.8°E) and Shanghai (31.4°N , 121.5°E) are used. Furthermore, satellite retrieved convective and non-convective precipitation rates (mm h^{-1}) for every 3 h in 0.25° spatial resolution are also utilized to calculate the

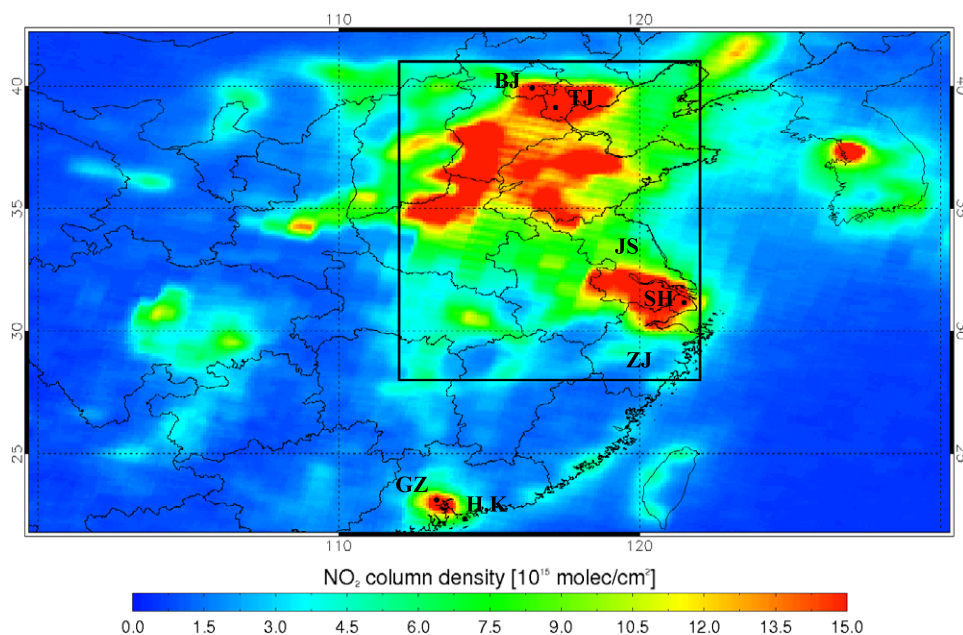


Figure 1. Average tropospheric NO_2 columns over East China measured by GOME-2 for May–October 2010 (the Expo period). The cities Beijing (BJ), Tianjin (TJ), Shanghai (SH), Guangzhou (GZ) and Hong Kong (HK) and the provinces Jiangsu (JS) and Zhejiang (ZJ) are marked.

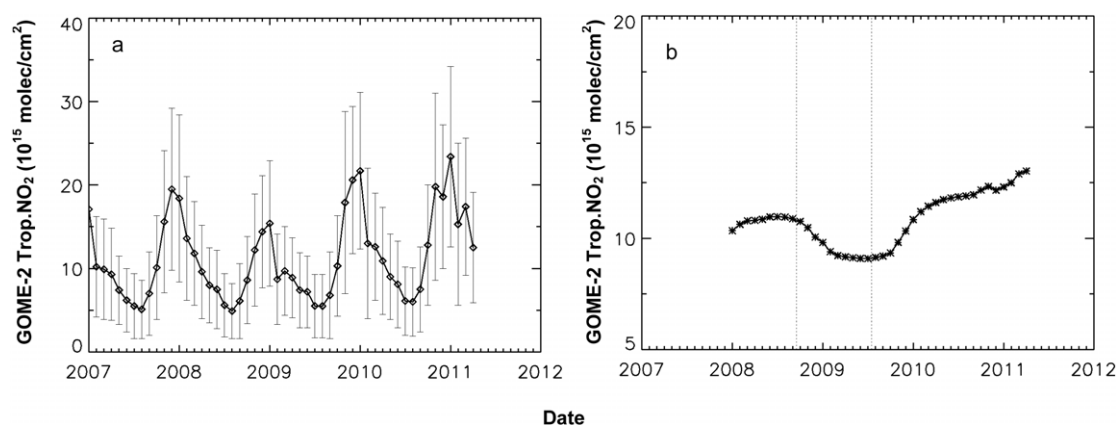


Figure 2. (a) Monthly averages of tropospheric NO_2 columns measured by GOME-2 over northeast China (see box in figure 1) from January 2007 to April 2011. (b) Shows a 12-month moving average of tropospheric NO_2 columns (each data point represents the mean average over the prior year).

average precipitation over Shanghai (30.6° – 31.4°N 121.1° – 121.9°E) from May to October in the years 2007–10 by assuming the precipitation rate is constant during a 3-h interval. The details about precipitation rate retrieval using passive microwave satellite can be found in Ferraro *et al* (1997, 2000) and Joyce *et al* (2004).

3. Results and discussion

In order to analyze the effect of the ECMs on the air quality during the Expo 2010, two periods are defined: the Expo period (May–October 2010) when all the ECMs were in effect and the post-Expo period (November 2010–April 2011) when short-term ECMs were lifted. May to October 2007–9 served as a

reference for the Expo period. Similarly, November to April 2007–10 served as a reference for the post-Expo period.

The GOME-2 tropospheric NO_2 distribution for the Expo period shows high tropospheric NO_2 columns above large urban and industrial areas such as Bohai Economic Rim including Beijing and Tianjin, the Yangtze River Delta including Shanghai, Zhejiang and Jiangsu Provinces and the Pearl River Delta including Guangzhou and Hongkong (figure 1). The monthly averages and 12-month moving average of GOME-2 NO_2 columns over Northeast China from January 2007 to April 2011 are shown in figure 2. Apart from the economic recession period (from late 2008 to the first half of 2009, see figure 2(b)), a clear increase of tropospheric NO_2 is found from 2007 to 2011 (the effect of the economic

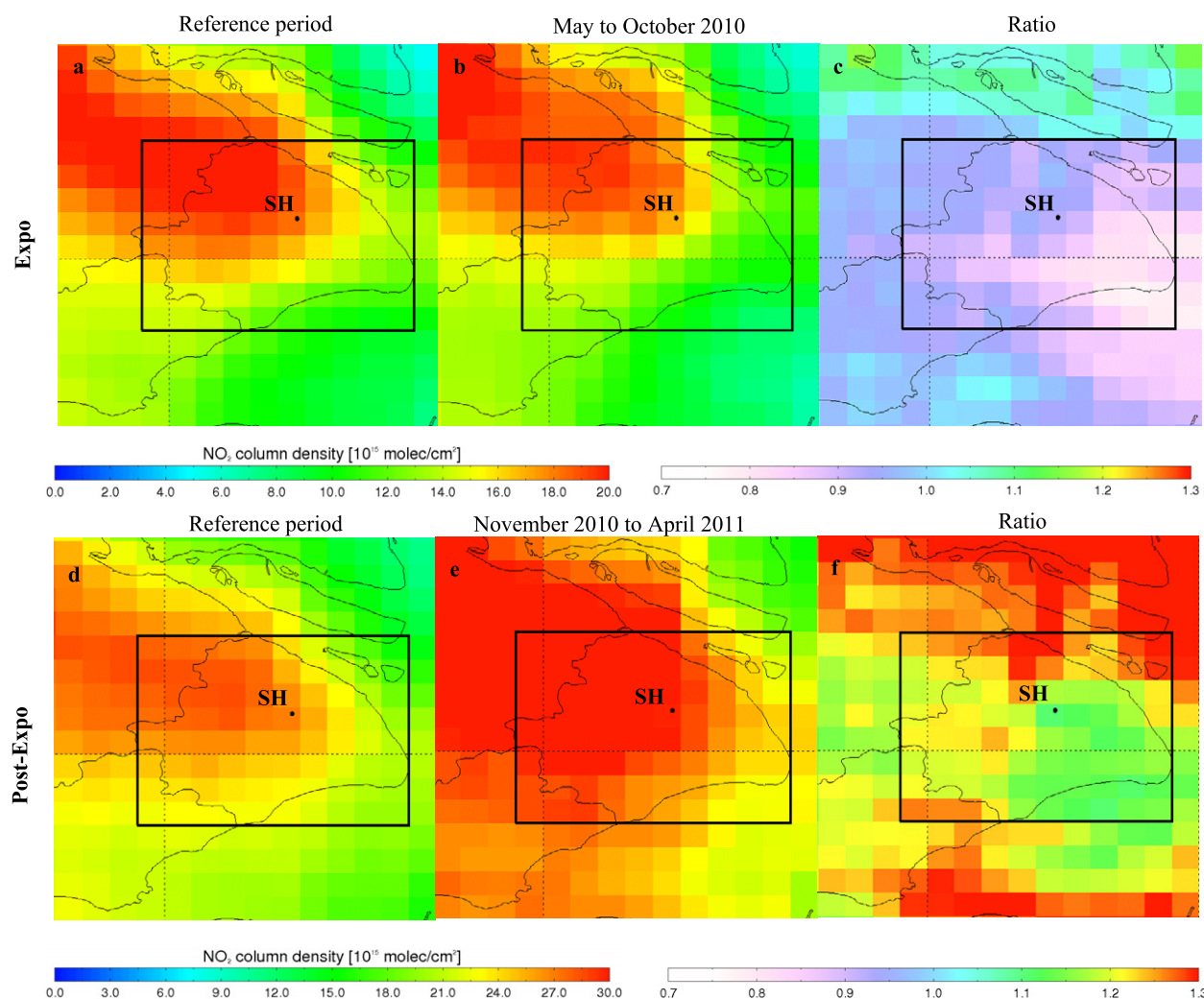


Figure 3. Average tropospheric NO_2 columns during the Expo period (b) and the post-Expo period (e). 18-month averages of tropospheric NO_2 columns for the corresponding references for the Expo period ((a) May–October 2007–9) and the post-Expo period ((d) November–April 2007–10) are also shown. The ratios of NO_2 columns between the Expo, post-Expo and references are shown in (c) and (f). A ratio of less than 1 indicates more NO_2 in the reference period. During the Expo period, significant NO_2 reduction (c) is found around Shanghai (SH).

recession on air pollutants over Northeast China is discussed in Lin *et al* (2010)). The strong increase of tropospheric NO_2 over the urban areas of China from 1994 to 2006 has been discussed by Richter *et al* (2005) and van der A *et al* (2006).

The GOME-2 tropospheric NO_2 columns for the Expo and the post-Expo periods are compared with those for the reference periods over Shanghai (see figure 3). The ratios of NO_2 columns between 2010 and the reference period show a reduction of NO_2 during the Expo period over Shanghai. Compared to previous years, tropospheric NO_2 columns over Shanghai decreased by about 8% during the Expo period. Figure 3 also shows that the tropospheric NO_2 columns increased by about 20% during the post-Expo period, compared to the reference period. As mentioned before, the yearly increase of the tropospheric NO_2 columns over Shanghai was about $20\% \pm 6\%$ from 1996 to 2005 (van der A *et al* 2006) and from 2007 to 11 the tropospheric NO_2 columns also increased by about 20% over Northeast China. The NO_2 increase during the post-Expo period is consistent with the NO_2 trend over Shanghai during 1996–

2005 and over Northeast China during 2007–11. It is interesting to compare the reductions of NO_2 for the Expo to the NO_2 reductions during the Beijing Olympic Games (Witte *et al* 2009). It was concluded that during the Olympic Games short-term ECMs, especially removal of half of the cars from the road, contributed to a decrease of 43% in NO_2 columns over Beijing. For the Expo, we did not find such a large NO_2 decrease, which is possibly related to the absence of very strict short-term traffic control measures over Shanghai and the surrounding areas due to the long duration of the Expo (6 months). Moreover, the meteorological conditions during the 2008 Beijing Olympic Games were atypical and were favorable to reductions of tropospheric NO_2 columns (Mijling *et al* 2009), while the meteorological conditions had no clear influence on the changes of air pollutants during the Expo (see below).

In situ NO_2 measurements derived from NO_2 API for the period May 2007 to April 2011 have been used for the comparison with the GOME-2 measurements. Figure 4 shows a scatter plot of the monthly average *in situ* NO_2

Table 1. Tropospheric NO₂ columns (10^{15} molec cm⁻²) and 1- σ standard deviation over Shanghai (30.7°–31.5°N, 120.9°–121.9°E, see the box in figure 3) as measured by GOME-2. *In situ* NO₂ concentrations ($\mu\text{g m}^{-3}$) and 1- σ standard deviation over Shanghai as measured by the Shanghai Environmental Monitoring Center (SEMC). Tropospheric NO₂ columns and *in situ* NO₂ concentrations are given for the periods May–October 2010 (Expo), November 2010–April 2011 (post-Expo) as well as for the reference period (2007–9).

	GOME-2					<i>In situ</i> measurements				
	2007–9		2010		Diff (%)	2007–9		2010		Diff (%)
	Mean	σ	Mean	σ		Mean	σ	Mean	σ	
Expo	14.3	3.5	13.1	3.7	–8	46.3	6.3	41.6	6.2	–10
Post-expo	22.9	3.3	27.5	4.2	20	57	8.6	65.3	7.8	15

Table 2. AOT and 1- σ standard deviation over Shanghai (see circle in figure 5) and Shanghai and the surrounding areas (see the box in figure 5) as measured by MODIS. AOT are given for the periods May–October 2010 (Expo) and November 2010–April 2011 (post-Expo), as well as the relative difference compared to the reference period (2007–9).

	Over Shanghai					Over Shanghai and the surrounding areas				
	2007–9		2010		Diff (%)	2007–9		2010		Diff (%)
	Mean	σ	Mean	σ		Mean	σ	Mean	σ	
Expo	0.91	0.28	0.78	0.24	–14	0.86	0.26	0.68	0.23	–21
Post-Expo	0.73	0.21	0.90	0.27	23	0.66	0.19	0.78	0.25	18

concentrations and GOME-2 tropospheric NO₂ columns. A high correlation (correlation coefficient up to 0.83) between satellite and *in situ* measurements is found. Table 1 lists the average NO₂ concentrations and columns observed by *in situ* and satellite measurements for the Expo, the post-Expo and the corresponding reference periods. The *in situ* measurements indicate that NO₂ concentrations decreased by about 10% during the Expo and increased by about 15% after the Expo. GOME-2 observed an 8% reduction in the tropospheric NO₂ columns during the Expo and a 20% increase after the Expo, compared to the reference periods, respectively. Similar results were reported by a post-Expo workshop report (CAI-Asia 2011) based on ground-based measurements. Both the satellite and *in situ* measurements indicate that the short-term ECMs implemented in Shanghai were effective in reducing the NO_x concentrations during the Expo. The lifting of short-term ECMs after the Expo resulted in a rebound in NO_x pollution. The reduction of NO₂ over a larger region including Shanghai and the surrounding provinces is not so clear because the traffic control measures might not be applied in the surrounding provinces.

To estimate the effect of ECMs on the aerosol loading over Shanghai, average Aqua/MODIS AOT during the Expo period and the corresponding reference period are compared in figure 5. During the Expo period, the AOT decreased by about 14% over Shanghai (circle in figure 5) compared to the reference period. Similar reductions in the PM₁₀ concentrations in Shanghai during the Expo period were reported by a Mid-Expo Air Quality Report (CAI-Asia 2010). The results showed that PM₁₀ concentrations decreased by about 12% during the Expo, compared to the same months (May–July) from 2001 to 2009. Figure 5 and table 2 illustrate that after the Expo, there was an increase of about 23% in the AOT over Shanghai, compared to the reference period. The monthly mean time series of AOT over Shanghai from May 2010 to April 2011 and the reference period are plotted in

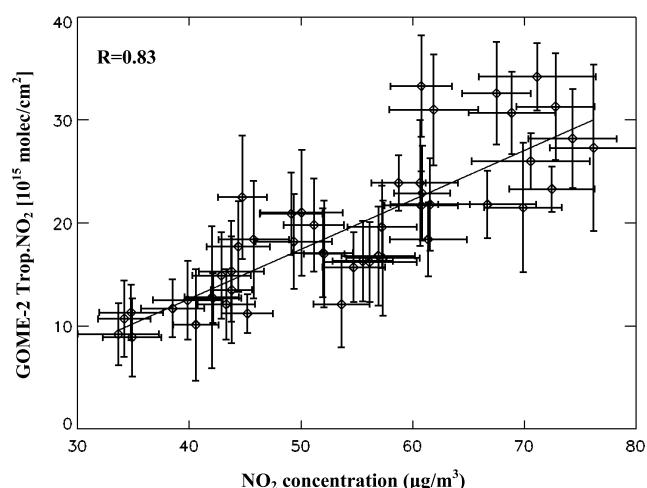


Figure 4. Scatter plot of the monthly mean *in situ* NO₂ ($\mu\text{g m}^{-3}$) concentrations and GOME-2 tropospheric NO₂ columns (mol cm^{-2}) over Shanghai from May 2007 to April 2011.

figure 6. AOT reduced in all months except October during the Expo and increased again during the post-Expo period. It is likely that the double increase in visitors and relatively loose ECM implementation in October (the last month of the Expo) contributed to the larger AOT compared to the reference period. The observed reduction in aerosol loading is most likely related to the short-term ECMs implemented over Shanghai during the Expo period.

Shanghai's neighboring provinces Zhejiang and Jiangsu, which are becoming rapidly industrialized and are highly urbanized, have a large impact on the air quality in Shanghai (UNEP 2010). Therefore, joint pollution prevention and ECMs based on the cooperation platform of Shanghai and the surrounding provinces were in effect during the Expo period. To check the effect of these joint ECMs, an analysis domain (29°–32°N, 120°–122°E) including Shanghai and the

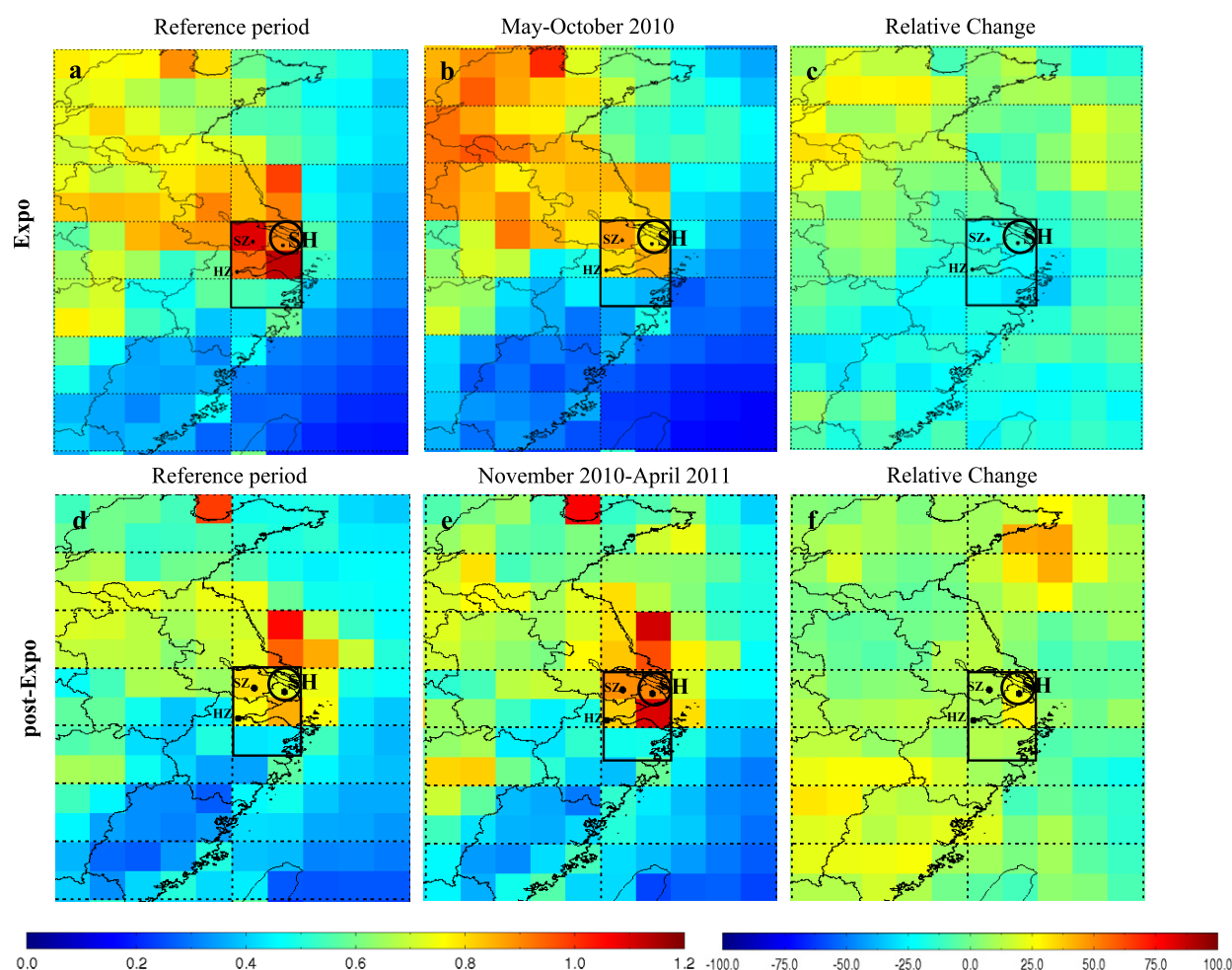


Figure 5. Mean AOT during the Expo (b) and post-Expo periods (e) as measured by MODIS. 18-month averages of AOT for the references for the Expo period ((a) May to October 2007–9) and the post-Expo period ((d) November–April 2007–10) are also shown. During the Expo period, significant AOT reduction (c) is found around Shanghai (SH), Suzhou (SZ) and Hangzhou (HZ). The relative change is given in per cent; negative values indicate a larger AOT in the reference period. The circle represents Shanghai while the box indicates Shanghai and the surrounding areas.

neighboring provinces was defined (box in figure 5). AOT values over this domain for the Expo and post-Expo periods are compared with those during the same months in the reference period, as listed in table 2. AOT reduction during the Expo period is about 21% and AOT increase after the Expo is about 18%, relative to the reference period. This may be a consequence of joint ECMs implemented in Shanghai and the surrounding provinces during the Expo period.

Figure 7 shows monthly averages of MOPITT CO concentrations at 700 hPa over Northeast China. In contrast to NO_2 (figure 2), there is no significant increase of CO concentrations from 2007 to 2011. Similarly to NO_2 , the effect of economic recession on CO concentrations is visible from late 2008 to the first half of 2009. For the Expo analysis, a larger region (29° – 32°N , 120° – 122°E) including Shanghai and the neighboring areas is used because CO has longer chemical lifetimes in the troposphere and enhanced concentrations may be found further away from the emission sources (Witte *et al* 2009). The relative changes in CO concentrations between the Expo period and the reference period are shown in figure 8. CO concentrations over Shanghai and the neighboring areas (box

in figure 8) decreased by about 12% during the Expo period, compared to the reference years. It is interesting to mention that in contrast to Shanghai, the large urban areas located in the north of China (i.e. Beijing and vicinity) where no ECMs were implemented showed an increase in the CO concentrations.

The monthly mean time series of CO from May 2010 to April 2011 and the reference period over Shanghai and neighboring areas are plotted in figure 9. MOPITT CO exhibits a seasonal variation (minimum in summer) in Shanghai, which is similar to that of CO ground-based measurements (Ran *et al* 2009). The monthly mean CO in figure 9 shows low CO concentrations during the Expo period especially from July to September, relative to the past three years. After the Expo, the CO concentrations are similar to those during the reference period (2007–9). The reductions of CO reflect the efficiency of the ECMs imposed on industry and agricultural burning in Shanghai and the surrounding regions during the Expo period.

It should be noted that we have used average data for a longer time period in our study, which reduces the error. We do not expect that the error in the satellite measurements will have a large impact on the analysis of the effectiveness of the ECMs.

Table 3. Meteorological data at Hongqiao airport, Shanghai (31.2°N, 121.3°E). Mean temperature, relative humidity, mean precipitation amount per month, prevailing wind direction, wind speed (including 1- σ standard deviation) and mean number of rainy days per year are given for the Expo period (May–October 2010) as well as for the reference period (2007–9). The 30 years (1971–2000) climatological data are also listed.

	Mean temperature (°C)	Relative humidity	Mean precipitation amount (mm/month)	Mean number of rainy days (yr ⁻¹)	Prevailing wind direction	Wind speed (km h ⁻¹)
Reference period	25.2 \pm 3.3	70 \pm 4.2	158 \pm 78	71	SE SSE	11.0 \pm 1.3
Expo 2010	24.9 \pm 4.5	69 \pm 3.6	120 \pm 55	69	SE SSE	10.7 \pm 0.8
Climatological data ^a	23.2	79	131	69	SE	10.3

^a Precipitation data come from the China Meteorological Administration. Other data come from Solar and Wind Energy Resource Assessment (SWERA).

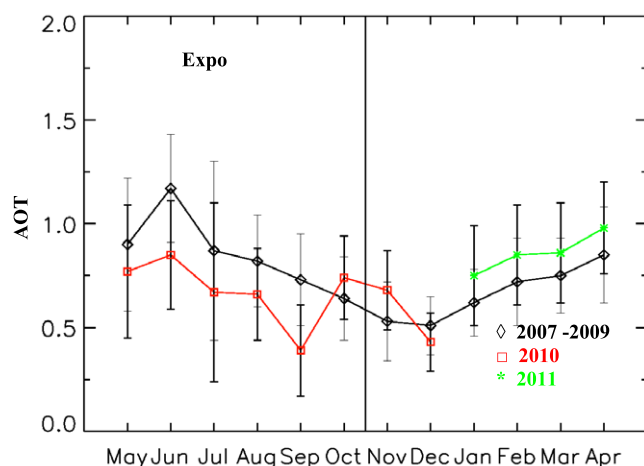


Figure 6. Time series of monthly mean AOT over Shanghai (see the circle in figure 5) measured by MODIS from May 2010 to April 2011 and the reference period (2007–9). The vertical bars denote the 1- σ standard deviation.

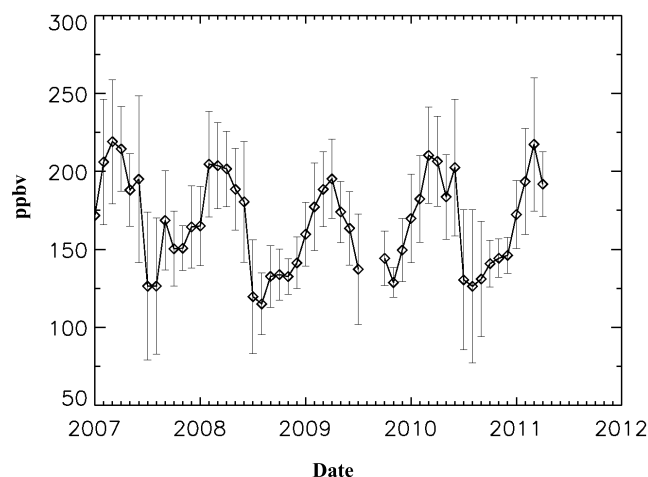


Figure 7. Monthly averages of CO concentrations measured by MOPITT over Northeast China (see the box in figure 1) from January 2007 to April 2011.

To investigate the effect of meteorological conditions on the changes in NO₂, aerosol loading and CO as described above, precipitation, temperature and wind data for Hongqiao airport, Shanghai during the Expo period and the reference period have been used. In addition, 30 years (1971–2000) of climatological data for the Shanghai area are also listed in table 3. It is shown that the meteorological conditions, including prevailing wind direction, mean precipitation amount per month and mean number of rainy days per year, during the Expo and the reference period in Shanghai were typical, compared to the climatological data in the 30 years. In addition, we checked the meteorological data from another two weather stations situated at Pudong airport, Shanghai and Shanghai. The meteorological conditions during the Expo and the reference period in these two weather stations are also typical, compared to the climatological data. A number of studies (Ding *et al* 2008, Zhao *et al* 2010, Zhang *et al* 2010a) have found that in May–August the Asian summer monsoon affects the air quality over eastern China by influencing transport, chemical reactions and deposition of air pollutants. To investigate the potential effect of the East Asian summer monsoon (EASM) strength on interannual variations of air pollutants over Shanghai, EASM indices from 2007 to 2010 are used (Li and Zeng 2003). Based on the results of Zhang

et al (2010a), the high aerosol pollution over East China is expected due to a relative weak summer monsoon in 2010. In addition, satellite retrieved precipitation data show that the total precipitation amount (about 720 mm) during the Expo period is smaller than for the same months in 2007 (about 1200 mm). Improved air quality in Shanghai during the Expo period is found, although a lower relative humidity and rainfall, which are favorable for air pollutant accumulation, occurred. Therefore we do not expect that the meteorological conditions had a significant impact on the improved air quality in Shanghai during the Expo period.

It is important to assess the consistency between the observed improvements in air quality and the emission reductions due to the control measures during the Expo. However, quantitative results on the emission reductions are not publicly available. The latest emission inventory over Shanghai was developed by Huang *et al* (2011) for the year 2007. It is difficult to compare the emission and satellite observations due to the lack of recent emission data. Zhang *et al* (2010b) are developing a fast method for estimating China's monthly NO_x emissions by integration of the bottom-up method and OMI observed NO₂ trends. In the future, we plan to make comparisons between these up-to-date emission inventory data and GOME-2 NO₂ measurements.

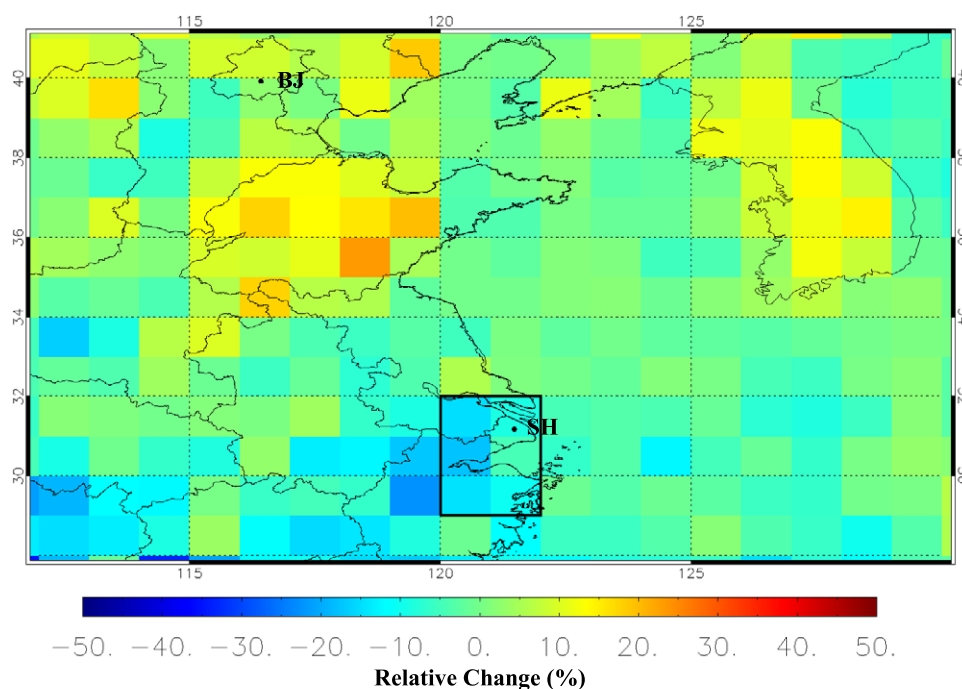


Figure 8. Relative changes in CO concentrations (in per cent) between the Expo period (May–October 2010) and the reference period (2007–9) for Shanghai and the surrounding areas (box). SH represents Shanghai and BJ represents Beijing.

4. Conclusion

We present a space-based assessment of the atmospheric composition changes in major air pollutants in Shanghai during and after the Expo in 2010. The GOME-2 measurements show 8% reduction of tropospheric NO_2 during the Expo period but 20% increase in Shanghai during the post-Expo period, compared to the same months in previous years. A high correlation (correlation coefficient up to 0.83) between the GOME-2 tropospheric NO_2 columns and *in situ* NO_2 concentrations is found. The analysis of the MODIS aerosol optical thickness in Shanghai shows an AOT reduction of 14% during the Expo period and a significant AOT increase of 23% after the Expo. A 12% reduction of the CO concentration at 700 hPa over Shanghai and the surrounding areas is found by MOPITT during the Expo period. The meteorological conditions do not have a significant impact on the air quality in Shanghai during the Expo. These results indicate that the air quality measures enforced by the Shanghai government were effective in Shanghai during the Expo period. Moreover, we find an AOT reduction of 21% over a wider region (including part of Jiangsu and Zhejiang Provinces) during the Expo period, which reflects the efficiency of the joint pollution control measures imposed by Shanghai and the surrounding provinces. The lifting of short-term ECMs such as access restriction of trucks and old cars into Shanghai and suspending work at factories and construction sites most likely contributed to the NO_2 and AOT increase after the Expo. Therefore, more stringent and consistent controls are needed to further improve the air quality in Shanghai and the surrounding regions. Our study demonstrates that satellite observations can be used to monitor and quantify air quality changes in megacities.

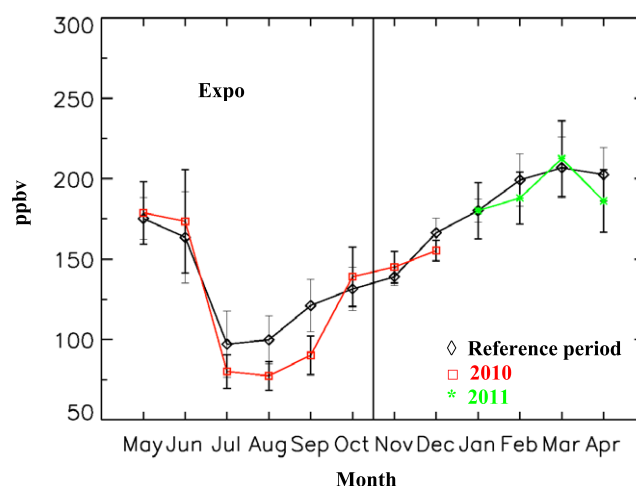


Figure 9. Time series of monthly mean CO concentrations (ppbv) at 700 hPa over Shanghai and the neighboring areas (see the box in figure 8) from May 2010 to April 2011 and for the reference period (2007–9).

Acknowledgments

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